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TN-9

Transition-State Theory of the Linear Rate of  
Decomposition of Ammonium Perchlorate\*

by

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FC

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\* \* \* \*

Abstract

The experimental data of Bircumshaw and Newman are analyzed in terms of a linear rate of progression of the interface between residue and undecomposed crystal. Linear decomposition rates corresponding to given temperatures are derived directly from the maximum rate portions of the sigmoid curves of product pressure versus time. It is proposed that in the temperature range 220°C to 280°C, the decom-

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\* This work was supported under Contract AF18(600)-1026 by the United States Air Force, through the Office of Scientific Research of the Air Research and Development Command OSR-TN-55-142.

position interface travels exclusively through the disordered material between the mosaic blocks of the crystal and does not penetrate the interior of these blocks. Absolute rate treatments in the manner of Laidler, Glasstone, and Eyring are presented for each of the two crystal forms (orthorhombic and cubic). These treatments are similar to those proposed for the sublimation of ionic solids and the vaporization of solid ammonium chloride, respectively.

Introduction

Bircumshaw and Newman<sup>1</sup> have recently summarized the results of an

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<sup>1</sup> L. L. Bircumshaw and E. H. Newman, Proc. Roy. Soc. (London), A227,  
115-132, 228-241 (1954).

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exceptionally detailed investigation of the kinetics of decomposition  
of ammonium perchlorate. The present writers sometime ago obtained a  
report<sup>2</sup> of well over a hundred pages containing the excellent original

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<sup>2</sup> L. L. Bircumshaw and E. H. Newman, Interim Report, March, 1951.

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data which facilitated the following theoretical analysis. The present  
paper is based upon a discussion<sup>3</sup> originally presented in 1952 and re-

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<sup>3</sup> R. D. Schults and A. O. Dekker, "The Kinetics of Decomposition of  
Ammonium Perchlorate" presented at the 122nd National Meeting,  
American Chemical Society, Atlantic City, New York, September, 1952.

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cently modified in the light of recent studies on the linear vaporiza-

sation rate of ammonium chloride<sup>4,5</sup> and on the sublimation rates of

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<sup>4</sup> R. D. Schults and A. O. Dakker, "The Absolute Thermal Decomposition Rates of Solids. Part I," in the Fifth International Combustion Symposium (1954), Reinhold Publishing Company, New York, (1955).

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<sup>5</sup> R. D. Schults and A. O. Dakker, to be published. OSR-TN-55-141.

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molecular<sup>6</sup> and ionic crystals.<sup>7</sup>

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<sup>6</sup> R. D. Schults and A. O. Dakker, J. Chem. Phys. in press. OSR-TN-54-367.

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<sup>7</sup> R. D. Schults and A. O. Dakker, to be published. OSR-TN-55-138

By a series of excellent photomicrographs on individual crystals of ammonium perchlorate, Bircumshaw and Newman<sup>1</sup> demonstrated that the slow decomposition at 230°C proceeds by the formation of opaque spots (i.e., nuclei) on the crystal surface. These spots then grow in size and eventually coalesce to form a continuous opaque region whose boundary with the transparent region was observed to move uniformly inward toward the center of the crystal. When the boundary reaches the center of the crystal, decomposition ceases, leaving a porous pseudomorph which is still pure ammonium perchlorate but which has a density only 70% of that of the original crystal.

In the following discussion, it is shown that a single consistent treatment of the kinetic data can be made in terms of the linear rate of progression of the interface between partially decomposed and un-decomposed crystal. A modification of a treatment by Mott<sup>8</sup> is used to

<sup>8</sup> N. F. Mott, Proc. Roy. Soc. (London), A172, 325 (1939).

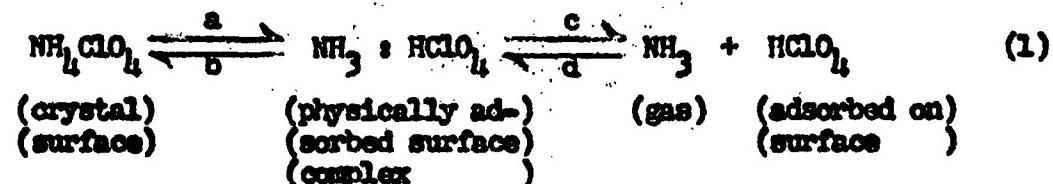
analyze the acceleratory (or nucleation) period, and a modification of a treatment by Topley and Hume<sup>9</sup> is used to analyze the deceleratory (or

<sup>9</sup> B. Topley and J. Hume, Proc. Roy. Soc. (London), A120, 211 (1929).

post-coalescence) period. An explanation for the observed cessation of the reaction at 30% completion is proposed on the basis of the concept of mosaic structure in crystals. The experimental linear rates derived by this analysis provide a basis for a transition-state absolute rate treatment in the manner of Glasstone, Laidler, and Eyring. These latter calculations suggest that the intermosaic material of the orthorhombic crystal decomposes below 250°C via a primary rate-controlling step requiring the attainment of nearly free rotation of the perchlorate ion. On the other hand, the intermosaic material of the cubic crystal appears to decompose above 250°C via a rate-controlling step which involves desorption of a loosely bound NH<sub>3</sub>:HClO<sub>4</sub> complex from its physically adsorbed state at the decomposition interface.

Theory of the Nucleation Process in the Acceleratory Period

Bircumshaw and Newman<sup>1,2</sup> have suggested that the formation of centers of decomposition on the crystal surface may be associated with the formation of free adsorbed perchloric acid. To support this hypothesis, they have demonstrated that the induction period for decomposition is considerably shortened by crystallizing some of the salt with perchloric acid as a 2% impurity. Moreover, they find that the induction period is considerably lengthened by a small pressure of ammonia over the salt, presumably caused by the neutralization of adsorbed perchloric acid. Accordingly, the following mechanism is assumed for the nucleation process:



state  
symbol (ss) (ad) (g) (ad)

Let  $ds/dt$  be the rate of escape of  $\text{NH}_3$  (g) from the surface of the crystal in molecules  $\text{sec}^{-1} \text{cm}^{-2}$ . As a first approximation, the back reactions (1b) and (1d) are neglected and reaction (1c) is assumed to be rate controlling, so that

$$\frac{ds}{dt} = k_c (\text{NH}_3 : \text{HClO}_4)_{\text{ad}} = k_s \quad (2)$$

where  $k_c$  is the specific rate constant for reaction (1c) and where  $k_s$

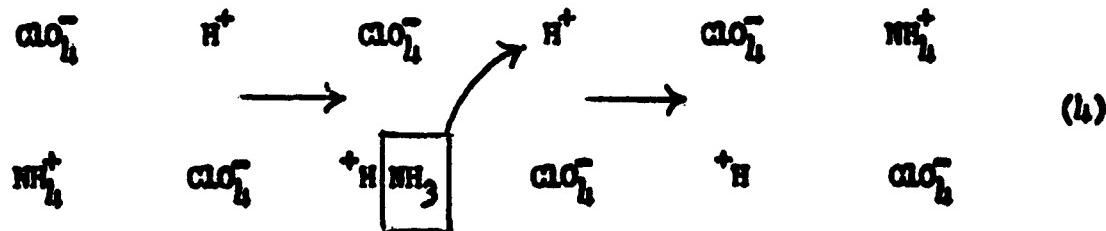
is a combination constant. (The alternate assumption that reaction (1a) is rate-controlling will not affect the mathematical form of the decomposition pressure-time relationship (13) below.) Assume in this first approximation that the rate of escape of perchloric acid from the surface is negligible. Assume also that the time required to attain temperature equilibrium is negligible compared to the duration of the nucleation period. At time  $t$  after start of heating, the concentration of perchloric acid in the surface is

$$(\text{HClO}_4)_{\text{ad}} = s = K_s t \quad (3)$$

provided that no adsorbed  $\text{HClO}_4$  or  $\text{NH}_3$  is present prior to  $t = 0$ . A nucleus will be considered to be in existence when a certain number,  $j$ , of  $\text{HClO}_4$  (ad) molecules have migrated to a potential nucleus site (i.e., surface discontinuity) and have decomposed to leave a surface hole. The mobility of the adsorbed perchloric acid could be the result of a surface lattice migration process of a type discussed by Macdonald.<sup>10</sup> For

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<sup>10</sup> J. Y. Macdonald, Trans. Far. Soc., 47, 860-863 (1951).  
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$\text{NH}_4\text{ClO}_4$  the migration process might be visualized as



The formation of an empty space in the surface lattice caused by a decomposition reaction of  $j$  molecules of  $\text{HClO}_4$  at a potential nucleus site should loosen the lattice restraints on the immediately adjacent ions, thereby permitting them to enter decomposition reactions. (This situation is comparable to the calcium carbonate decomposition discussed by Langmuir.<sup>11</sup> The latter used the phase rule to show that the

<sup>11</sup> I. Langmuir, J. Am. Chem. Soc., 38, 2263-2267 (1916).

lattice vacancy left by the removal of a  $\text{CO}_2$  group weakens the bonds by which adjacent groups are held.) The rate of nuclei formation per unit area of crystal is then

$$\frac{dn}{dt} = k_n \gamma s^j = k_n \gamma K_s j_t j \quad (5)$$

where  $\gamma$  is the number of potential nucleus sites per unit area and  $k_n$  is the specific rate constant of the nucleation process.

It has been observed in many crystal decompositions that the radial growth rate ( $dr/dt$ ) of a nucleus is constant under isothermal conditions and varies with temperature  $T$  according to the equation

$$B = dr/dt = B_0 \exp (-E/RT) \quad (6)$$

At the time  $\tau'$ , the radius of a nucleus born at time  $t$  is

$$r = B (\tau' - t) \quad (7)$$

Both  $\tau'$  and  $t$  are measured from the commencement of heating.

The volume of a hemispherical nucleus is

$$V = (2/3) \pi r^3 (\tau' - t)^3 \quad (8)$$

and the total volume  $V_n$  of all  $n$  nuclei existing at anytime  $\tau'$  before coalescence (i.e., before appreciable interference of decomposition zones occurs) is

$$V_n = \int_0^n (2/3) \pi r^3 (\tau' - t)^3 dt \quad (9)$$

where  $dt$  is given by equation (5). Hence

$$V_n = \int_0^{\tau'} (2/3) \pi B^3 k_n r K_s^j t^j (\tau' - t)^3 dt \quad (10)$$

Integration gives

$$V_n = \frac{4\pi B^3 k_n r K_s^j}{(j+1)(j+2)(j+3)(j+4)} \tau'^{j+4} \quad (11)$$

If it is assumed that perchloric acid decomposes by a bimolecular reaction at a potential nucleus site,  $j = 2$ , so that

$$v_n = (\pi r^3 k_n \gamma R^2 / 90) T^6 \quad (12)$$

In the absence of secondary reactions at time ( $t$ ), the pressure ( $p$ ) of decomposition products above the salt is proportional to  $v_n$ , so that

$$p = (C \pi r^3 k_n \gamma R^2 / 90) T^6 \quad (13)$$

where  $C$  is a constant of proportionality. Equation (13) is identical in form to the power expression,  $p = kt^x$  (where  $x = 6.2 \pm 0.5$ ) which Bircumshaw and Newman<sup>2</sup> found to hold for the acceleratory period at  $220 \sim 275^\circ\text{C}$ . Secondary reactions in the gaseous decomposition products which involve volume changes will not affect the experimental value of the exponent  $x$  provided that the final decomposition is attained in a time which is either very small or very large compared to the duration of the acceleratory period.

The above calculations suggest that some kind of bimolecular reaction is responsible for the formation of a nucleus but it is by no means certain that the reaction involves perchloric acid. An alternative assumption that a nucleus is formed by two holes (or even two charged particles) which migrate through the crystal lattice and coalesce at a discontinuity in the crystal would lead to a mathematical expression of the same form as equation (13). (See H. F. Mott<sup>8</sup>.)

The Maximum Rate Period

Once coalescence of the growing nuclei has occurred so that the surface is completely covered by a layer of residue, equation (13) is no longer valid. At this time, the reaction interfaces no longer increase in area. Instead, the resulting single interface decreases in area as it progresses toward the center of the crystal. Let the shape of a given crystal at coalescence time  $t_y$  be approximated as a sphere of radius  $r_y$ . The volume  $V_y$  of undecomposed crystal inside this sphere at time  $t_y$  is

$$V_y = (4/3)\pi r_y^3 \quad (14)$$

At the later time  $t$ , the volume  $V_t$  of undecomposed crystal is

$$V_t = (4/3)\pi \left[ r_y - B(t - t_y) \right]^3 \quad (15)$$

Differentiation gives

$$\frac{dV_t}{dt} = -4\pi B \left[ r_y - B(t - t_y) \right]^2 \quad (16)$$

The rate of increase of decomposition product pressure  $dp/dt$  is proportional to the rate of volume decrease  $-dV_t/dt$  and to  $Q$  the number

of crystals assumed uniform in size and shape, so that

$$\frac{dp}{dt} = 4\pi QCG \left[ r_y - R(t - t_y) \right]^2 \quad (17)$$

where  $G$  is a proportionality constant. The maximum rate occurs at the time  $t = t_y$  so that

$$(dp/dt)_y = 4\pi QCG r_y^2 \quad (18)$$

The number of crystals  $Q$  in a fixed initial weight  $W$  of uniform  $\text{NH}_4\text{ClO}_4$  crystals (assumed spherical in shape) is

$$Q = \frac{3W}{4\pi r_0^3 \rho} \quad (19)$$

where  $r_0$  is the initial crystal radius and  $\rho$  its density.

Insertion of (19) into (18) gives

$$(dp/dt)_y = 3 \frac{WCG}{\rho} \frac{r_y^2}{r_0^3} \quad (20)$$

Let the difference between the initial radius of the crystal and the radius of the spherical reaction interface at coalescence be  $\delta$  so

that

$$r_y = r_0 - \delta \quad (21)$$

and

$$(dp/dt)_y \propto (r_0 - \delta)^2 / r_0^3 \propto (r_0^2 - 2r_0\delta + \delta^2) / r_0^3 \quad (22) \propto = \text{proportional to}$$

For large crystals,  $\delta$  is small compared to  $r_0$  so that

$$(dp/dt)_y \propto 1/r_0 \quad (23)$$

Thus, the maximum rate for a given mass of large  $\text{NH}_4\text{ClO}_4$  crystals should vary inversely as the initial crystal radius. Indeed, this is nearly the relationship observed by Bircumshaw and Newman<sup>2</sup> for crystals greater than 0.004 inches in diameter. Below this size, the maximum rate was found to decrease with decrease in diameter. This results from the fact that coalescence occurs at greater percentages of decomposition for the smaller particles (i.e.,  $\delta$  is no longer small compared to  $r_0$ ). Mampel<sup>12</sup>

12 K. L. Mampel, Z. Physik. Chem., A187, 43-57, 235-249 (1940).

reached a similar conclusion about the effect of decreased particle size on the rate of solid decomposition.

For a given batch of uniform crystals, the point of inflection of the commonly observed sigmoid decomposition pressure-time curves correspond approximately to  $t_y$ , the time of coalescence of the nuclei on the surface of the crystal. At time  $t = t_y$  the decomposition rate, in terms of fraction of original crystal volume  $V_0$ , is from equation (16)

$$\left( \frac{dV_t/V_0}{dt} \right)_y = -3B \frac{r_y^2}{r_0^3} \quad (24)$$

But  $V_0$  is proportional to  $p_f$ , the final decomposition pressure, so that (24) becomes

$$\left( \frac{dp/p_f}{dt} \right)_y = 3B \frac{r_y^2}{r_0^3} \quad (25)$$

The ratio of the volume  $V_y$  of undecomposed crystal to the original volume  $V_0$  is at time  $t_y$

$$\frac{V_y}{V_0} = \frac{r_y^3}{r_0^3} = \frac{p_f - p_y}{p_f} \quad (26)$$

The radius of the decomposition interface at time  $t_y$  is, therefore,

$$r_y = r_0 (p_f - p_y)^{1/3} p_f^{-1/3} \quad (27)$$

The maximum rate of linear progression of the decomposition interface,

$B = dr_y/dt$ , at time  $t_y$  is

$$B = \frac{r_0 (dp/dt)_y}{3p_f^{1/3} (p_f - p_y)^{2/3}} \text{ cm sec}^{-1} \quad (28)$$

where  $r_0$  = initial crystal radius cm

$(dp/dt)_y$  = slope at the point of inflection of  
sigmoid decomposition product  
pressure - time curve mm Hg sec<sup>-1</sup>

$p_y$  = decomposition product pressure at  
point of inflection mm Hg

$p_f$  = final product pressure (assuming  
no change in volume of system  
during run) mm Hg

By means of equation (28), experimental values of B (plotted in Figure 1 as  $\log_{10} B$  versus  $1/T$ ) were derived directly from the sigmoid p-t curves of the original Bircumshaw and Newman data<sup>2</sup> using their estimated mean value of  $r_0 = 1.98 \times 10^{-2}$  cm. Below 513°K the linear decomposition rate of the intermosaic material of the orthorhombic  $\text{NH}_4\text{ClO}_4$  crystal is given by

$$B_{\text{NH}_4\text{ClO}_4 \text{ (orthorhombic)}} = 1.5 \times 10^8 \exp(-31,600/RT) \text{ cm sec}^{-1} \quad (29)$$

At  $513^{\circ}\text{K}$ , the crystal of  $\text{NH}_4\text{ClO}_4$  assumes the cubic NaCl type lattice. Above this temperature, the linear decomposition rate of the intermoxic material of the cubic  $\text{NH}_4\text{ClO}_4$  crystal is

$$B_{\text{NH}_4\text{ClO}_4 \text{ (cubic)}} = 2.4 \times 10^1 \exp(-16,200/RT) \quad \text{cm sec}^{-1} \quad (30)$$

It is of interest to compare equation (29) with an equation<sup>7</sup> recently estimated for the maximum linear rate of advance in vacuo of the decomposition interface between  $\text{CaCO}_3$  and  $\text{CaO}$

$$B_{\text{CaCO}_3:\text{CaO}} = 7.7 \times 10^7 \exp(-37,600/RT) \quad \text{cm sec}^{-1} \quad (31)$$

It is also of interest to compare equation (30) with the equation for the linear rate of vaporization of ammonium chloride obtained by an analysis<sup>14</sup> of the experimental data of H. Spingler.<sup>13</sup>

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<sup>13</sup> H. Spingler, Z. Physik. Chem., B52, 90-106 (1942).  
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$$B_{\text{NH}_4\text{Cl}} = 1.2 \times 10^2 \exp(-13,500/RT) \quad \text{cm sec}^{-1} \quad (32)$$

The Deceleratory Period

It follows from the previous mathematical analysis that the equation of the deceleratory portion of the sigmoid  $p - t$  curve is

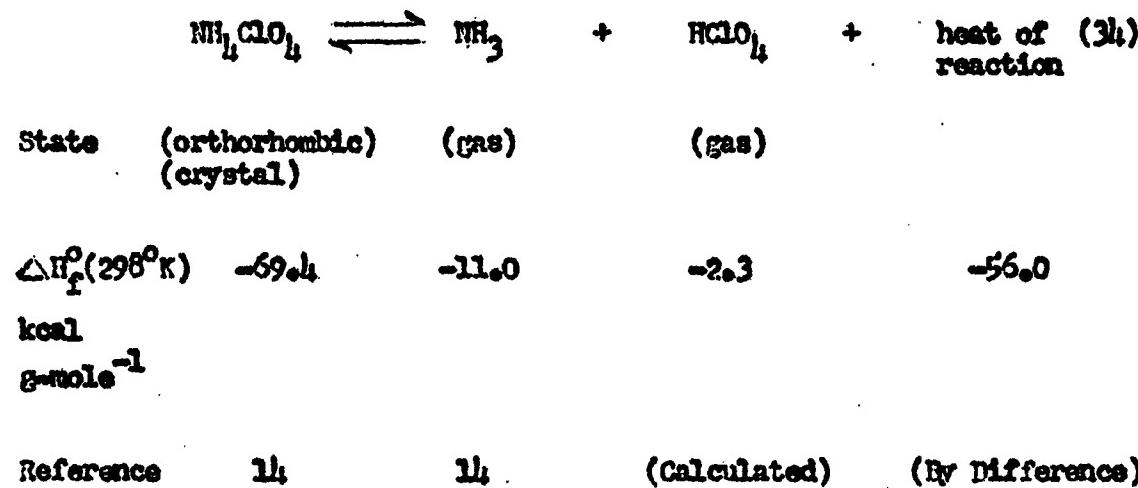
$$\frac{p_f - p}{p_y} = \frac{[r_y - B(t - t_y)]^3}{r_o^3} \quad (33)$$

where  $r_y$  is given by equation (27). Figures 2, 3, and 4 compare the deceleratory curves derived by equation (33) with the experimental curves. At  $215^\circ\text{C}$ , the agreement is excellent but becomes progressively poor with increasing temperature. The discrepancy at higher temperatures may be the result of an increase in the vaporization rate of the salt without oxidization-reduction reactions in the gas phase or perhaps may be the result of an impedance or hindering effect of the layer of residue on the escape of gaseous products from the decomposition interface.

The Thermodynamics of the Simple Dissociation Process

An enthalpy balance for the dissociation of orthorhombic ammonium

perchlorate to gaseous ammonia and perchloric acid may be written as



14 National Bureau of Standards, Circular 500 (1952).

A value of 8.8 koal g-mole<sup>-1</sup> for the enthalpy of vaporization of anhydrous perchloric acid was estimated from vapor pressure data<sup>15</sup> by

15 J. W. Mallor, "Comprehensive Treatise on Inorganic and Theoretical Chemistry," Longmans, Green and Company, (London), Vol. II, p. 377.

use of the Clausius-Clapeyron equation. This enthalpy of vaporization was added to the -11.1 koal g-mole<sup>-1</sup> heat of formation of  $\text{HClO}_4$  (liq) (Reference 14) to obtain the estimated value  $\Delta H_f^\circ(298^\circ\text{K}) \text{ HClO}_4 \text{ (gas)} \approx -2.3$  koal g-mole<sup>-1</sup>. Reaction (34), as written, is endothermic to the extent of about 56 koal g-mole<sup>-1</sup>. This value is somewhat uncertain

because the heat of aqueous solution of  $\text{HClO}_4$  (liq) is not known accurately.<sup>16</sup> Since the endothermicity of the simple dissociation process

<sup>16</sup> C. F. Goodeve and A. E. Le Marsh, J. Chem. Soc., 1516 (1937).

(3b) is much higher than the observed activation energies for the vaporization process, it follows that the latter must occur in stages rather than as a single step.

#### The Nature of the Residue

Garner and Hailes<sup>17</sup> have suggested that, in certain cases, solid

<sup>17</sup> W. E. Garner and H. R. Hailes, Proc. Roy. Soc. (London), A139, 576-595 (1933).

decomposition might proceed preferentially along the boundaries of the mosaic blocks comprising a crystal. If the decomposition paths at 215 to  $280^{\circ}\text{C}$  travel exclusively through the strained intermosaic lattice in  $\text{NH}_4\text{ClO}_4$  crystals and do not penetrate the interior of the mosaic blocks, the formation of a residue stable at these temperatures is understandable. The minimum size of the mosaic blocks in ammonium perchlorate may be estimated on the assumption that the thickness of the strained transition lattice is about equal to the side of a unit cell of the cubic lattice,

If the residue consists mainly of the original mosaic blocks with the intermosaic material removed, it follows that

$$\frac{\text{Mass residue}}{\text{Mass original crystal}} = \left[ \frac{D}{D+d} \right]^3 = 0.7 \quad (35)$$

where      D      is the side dimension of the mosaic block  
              d      is the thickness of the intermosaic layer  
              0.7      is the fraction of the original mass remaining  
                        after cessation of decomposition.

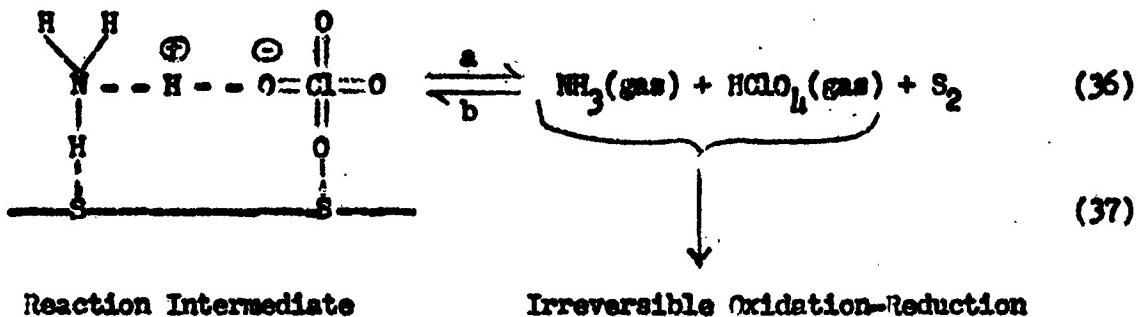
Setting d equal to 7.64 Å, the side dimension of the unit cell in cubic  $\text{NH}_4\text{ClO}_4$  (Reference 18), gives a minimum average value of about 62 Å for

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18 K. Herrmann and W. Illge, Z. Krist., 75, 41-66 (1931).

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the side dimension of a mosaic block or about 69 Å for the spacing of successive intermosaic layers.

Transition State Decomposition Rate Theory for  
Intermosaic Cubic  $\text{NH}_4\text{ClO}_4$

Assume that the final stages of the mechanism of decomposition of the intermosaic material in the cubic form of ammonium perchlorate is



where  $S_2$  is a dual adsorption site and where the reaction intermediate is a loose  $NH_3 : HClO_4$  complex which is physically adsorbed at the decomposition interface. Reactions (36a) and (36b) are similar to those assumed in a recently revised absolute rate treatment<sup>5</sup> of the ammonium chloride decomposition  $NH_4 Cl(s) \rightleftharpoons NH_3(g) + HCl(g)$ . A possibility exists, therefore, of analyzing the reverse reaction (36b) by a straightforward application of the absolute rate treatment formulated by Laidler, Glasstone, and Eyring<sup>19</sup> for a bimolecular surface reaction

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<sup>19</sup> See K. J. Laidler, "The Absolute Rates of Surface Reactions" in

Catalysis, Vol. I, Part 1, 195-243 (1954); P. H. Emmet, editor.

Reinhold Publishing Co., New York. See particularly pp. 214-217.

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proceeding by Langmuir-Hinshelwood mechanism. By analogy with the treatment for  $NH_4 Cl$ , the maximum exchange rate, reaction (36b), should be equal to the maximum forward rate of reaction (36a). Assuming the latter to be rate-controlling, the maximum decomposition rate of the

intermosaic material of the cubic form of ammonium perchlorate should correspond to the equation

$$\frac{-d(\text{NH}_4\text{ClO}_4)}{dt} = \left[ \text{NH}_3 \right]_{\text{g}} \left[ \text{HCl} \right]_{\text{g}} C_{S_2} \frac{kT}{h} \frac{P^*}{P_{\text{NH}_3(\text{g})} P_{\text{HCl}(\text{g})} P_{S_2}} e^{-E_0/RT} \quad (38)$$

ion-pairs  
 $\text{cm}^{-2} \text{ sec}^{-1}$

where

- $-\frac{d(\text{NH}_4\text{ClO}_4)}{dt}$  = the decomposition rate per unit area of exposed surface of intermosaic material ion-pairs  $\text{cm}^{-2} \text{ sec}^{-1}$
- $[\text{NH}_3]_{\text{g}}$  = steady state gas phase concentration of ammonia in contact with the reaction interface molecules  $\text{cm}^{-3}$
- $[\text{HClO}_4]_{\text{g}}$  = steady state gas phase concentration of perchloric acid in contact with the reaction interface molecules  $\text{cm}^{-3}$
- $C_{S_2}$  = concentration of bare dual adsorption sites  $\text{cm}^{-2}$
- $P^*$  = partition function of activated complex over all degrees of freedom except the vibrational mode included in  $kT/h$

$f_{\text{NH}_3(g)}$	= partition function of ammonia per unit volume of gas phase	
$f_{\text{HClO}_4(g)}$	= partition function of perchloric acid per unit volume of gas phases	
$f_{S_2}$	= partition function of a bare dual adsorption site	
$E_0$	= activation energy of surface reaction	calories g-mole <sup>-1</sup>
$kT/h$	= Eyring frequency for passage over potential energy barrier	sec <sup>-1</sup>

By a procedure nearly identical to that used for ammonium chloride<sup>5</sup> equation (38) may be simplified to

$$B_{\text{NH}_4\text{ClO}_4 \text{ (cubic)}} = \left( \frac{\rho}{M} \right)^{1/3} \frac{kT}{h} \frac{f^*(\text{trans})}{f(\text{NH}_3) f(\text{HClO}_4)} \cdot \left( \frac{E + E_{\text{NH}_3} + E_{\text{HClO}_4}}{RT} \right)^{1/2} \quad (39)$$

where

$kT/h$	= Eyring transition-state frequency for passage over a potential energy barrier	sec <sup>-1</sup>
$M$	= formula weight of $\text{NH}_4\text{ClO}_4$	g g-mole <sup>-1</sup>
$\rho$	= density of $\text{NH}_4\text{ClO}_4$ (cubic) $\approx 1.95$	g cm <sup>-3</sup>
$N$	= Avogadro's number	molecules g-mole <sup>-1</sup>

$f^*(\text{trans})$  = partition function for a one-dimensional translation motion of the center of gravity of the complex in the plane of the crystal surface.

As an approximation  $f^*(\text{trans}) \approx 1$

$f(\nu)$  = single mode vibrational partition function of the form  $\left[1-\exp(-h\nu/kT)\right]^{-1}$ . As an approximation  $f(\nu) \approx kT/h$

$\nu_{\text{NH}_3}$   
 $\nu_{\text{HClO}_4}$

= frequencies for translational oscillation of physically adsorbed ammonia and hydrogen chloride in the plane of the adsorbed layer at the decomposition interface

$E_0$  = activation energy for surface reaction

$\text{sec}^{-1}$

$E_{\text{NH}_3}$  = energy of adsorption of ammonia

$\text{calories g-mole}^{-1}$

$E_{\text{HClO}_4}$  = energy of adsorption of perchloric acid

$\text{calories g-mole}^{-1}$

Implicit in equation (39) is the assumption that the rotational oscillation of physically adsorbed  $\text{HClO}_4$  is nearly free gas-type rotation.

The frequencies  $\nu_{\text{NH}_3}$  and  $\nu_{\text{HClO}_4}$  may be estimated in the manner of Hill<sup>20</sup>

<sup>20</sup> T. L. Hill, J. Chem. Phys., 16, 181-189 (1948).

and Drenan and Hill<sup>21</sup> by use of the equation

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<sup>21</sup> J. W. Drenan and T. L. Hill, J. Chem. Phys., 17, 775-781 (1949).  
-----

$$\nu = (v_0/m s^2)^{1/2} = 1.025 \times 10^{13} (v_0/m s^2)^{1/2} \text{ sec}^{-1} \quad (39)$$

where

$\nu_x = \nu_y = \nu$  = translational oscillation frequency in the x  
or y directions in the plane of the physi-  
cally adsorbed layer

$v_0$  = maximum potential energy barrier to trans-  
lation in x or y direction

ergs

$m$  = mass of adsorbed molecule

g

$s$  = distance between potential minima along x or  
y axis of surface lattice (assumed simple  
cubic)

cm

$v_0$  = same as  $v_0$  except for unit

kcal g-mole<sup>-1</sup>

$M$  = molecular weight of adsorbed molecule

g g-mole<sup>-1</sup>

$S$  = same as  $s$  except for unit

Å

Hill<sup>20</sup> has estimated the potential barrier  $v_0$  to be about 0.3 - 1.0  
kcal g-mole. If  $\text{HClO}_4$  is adsorbed preferentially on a  $\text{NH}_4^+$  ion and

$\text{NH}_3$  is adsorbed preferentially on a  $\text{ClO}_4^-$  ion, the distance  $S$  should be about equal to the  $7.64 \text{ \AA}$  side dimension of the unit cell in cubic  $\text{NH}_4\text{ClO}_4$ . Thus, the estimated frequencies are

$$\nu_{\text{NH}_3} \approx 1.8 \text{ to } 3.3 \times 10^{11} \text{ sec}^{-1} \text{ (40)}$$

$$\nu_{\text{HClO}_4} \approx 0.7 \text{ to } 1.3 \times 10^{11} \text{ sec}^{-1} \text{ (41)}$$

As in the treatment for ammonium chloride

$$E_0 \approx 2v_0 \approx 600 \text{ to } 2000 \text{ calories g-mole}^{-1} \text{ (42)}$$

$$E_{\text{NH}_3} \approx \Delta H_{\text{cg}} \text{ NH}_3 - RT_{\text{cg}} \approx 6,60 \text{ calories g-mole}^{-1} \text{ (43)}$$

$$E_{\text{HClO}_4} \approx \Delta H_{\text{cg}} \text{ HClO}_4 - RT_{\text{cg}} \approx 10,700 \text{ calories g-mole}^{-1} \text{ (44)}$$

where  $\Delta H_{\text{cg}}$  signifies an enthalpy of sublimation measured at the temperature  $T_{\text{cg}}$ . Therefore, the theoretical value of  $E_{\text{NH}_4\text{ClO}_4}$  (cubic) at  $T_{\text{average}} = 532^\circ\text{K}$  is between

$$E_{\text{NH}_4\text{ClO}_4(\text{cubic})} = 5.5 \times 10^7 \exp(-17,800/RT) \text{ cm sec}^{-1} \text{ (45)}$$

Theory ( $v_0$  assumed to be  $0.3 \text{ kcal g-mole}^{-1}$ )

and

$$E_{\text{NH}_4\text{ClO}_4(\text{cubic})} = 1.6 \times 10^2 \exp(-19,200/RT) \quad \text{cm sec}^{-1} \quad (46)$$

Theory ( $v_0$  assumed to be 1.0 kcal g-mole<sup>-1</sup>)

in fair agreement with the experimentally derived value

$$E_{\text{NH}_4\text{ClO}_4(\text{cubic})} = 2.4 \times 10^1 \exp(-16,200/RT) \quad \text{cm sec}^{-1} \quad (47)$$

Experiment

Use of energies of liquefaction instead of energies of sublimation to approximate  $E_{\text{NH}_3}$  and  $E_{\text{HClO}_4}$  would have given an activation energy of 13,900 to 15,500 calories g-mole<sup>-1</sup> also in fair agreement with the experimental value. In these calculations the enthalpies of sublimation and liquefaction of ammonia were taken from a compilation by the U. S. Bureau of Standards.<sup>22</sup> The enthalpy of fusion of perchloric

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<sup>22</sup> U. S. Bureau of Standards, Circular 500 (1952).

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acid was estimated to be about 2.5 kcal g-mole<sup>-1</sup> by comparison with nitric, sulfuric, and phosphoric acid. The enthalpy of vaporization of perchloric acid was estimated above to be 8.8 kcal g-mole<sup>-1</sup> from vapor pressure data at 16 and 39°C.

Transition-State Decomposition Rate Theory for  
Intermosaic Orthorhombic  $\text{NH}_4\text{ClO}_4$

For the linear decomposition of the intermosaic material in orthorhombic  $\text{NH}_4\text{ClO}_4$ , the experimentally derived pre-exponential factor of  $1.5 \times 10^8 \text{ cm sec}^{-1}$  is about the same as for sublimation of simple ionic crystals and for the decomposition of calcium carbonate.<sup>7</sup> In these cases, the chief statistical difference between the initial and activated states appears to be that rotation or nearly free rotation is possible only in the activated state. Accordingly, it will be assumed that the formation of the activated complex for the decomposition of intermosaic orthorhombic  $\text{NH}_4\text{ClO}_4$  requires the attainment of an almost free rotational motion of the  $\text{ClO}_4^-$  ion at the decomposition interface. A reasonable estimate of the initial state torsional oscillation frequency of the  $\text{ClO}_4^-$  ion is about  $7.5 \times 10^{12} \text{ sec}^{-1}$  corresponding to a characteristic temperature  $\Theta = h\nu/k = 360^\circ\text{K}$ . It will be assumed, in accordance with a suggestion by Bircumshaw and Newman,<sup>1</sup> that the ammonium ion is rotating almost freely in the initial state in both orthorhombic and cubic  $\text{NH}_4\text{ClO}_4$ . Apropos of this assumption, the neutron diffraction experiments of Levy and Peterson,<sup>23</sup> the infrared spectra

23 H. A. Levy and S. W. Peterson, J. Chem. Phys., 21, 366 (1953);

J. Am. Chem. Soc., 75, 1536-1542 (1953).

studies of Plumb and Hornig,<sup>24</sup> and the Raman spectra studies of Couture-

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<sup>24</sup> R. C. Plumb and B. F. Hornig, J. Chem. Phys., 21, 366-367 and 1113  
(1953).

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Mathieu and Mathieu<sup>25</sup> provide evidence that one-dimensional rotation of

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<sup>25</sup> Le Couture-Mathieu and J. P. Mathieu, J. Chem. Phys., 49, 226 (1952).

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the  $\text{NH}_4^+$  ion is possible in the ammonium halides (i.e.,  $\text{ND}_4\text{Br}$ ,  $\text{ND}_4\text{I}$ ,  $\text{NH}_4\text{I}$ ) possessing the NaCl-type structure. Moreover, the neutron dif-  
fraction experiments<sup>23</sup> provide evidence for appreciable rotatory oscil-  
lation of the  $\text{NH}_4^+$  ion in  $\text{ND}_4\text{Br}$ . The fact that  $\text{ClO}_4^-$  is larger than either  
the  $\text{Br}^-$  or  $\text{I}^-$  ion makes nearly free rotation of  $\text{NH}_4^+$  ion in crystalline  
 $\text{NH}_4\text{ClO}_4$  a distinct possibility.

The attainment of the activated complex for decomposition probably  
also involves a translational motion of the  $\text{ClO}_4^-$  ion. In a manner analo-  
gous to that used for the escape velocity during sublimation,<sup>6,7</sup> the  
activated state translational motion of the  $\text{ClO}_4^-$  ion is divided into three  
components. The partition function for one of these components is in-  
cluded in the  $kT/h$  factor of the Eyring formulation of transition state  
theory. The other two components are assumed to be normal-state trans-  
lational lattice vibrations. It is further assumed that the translational  
lattice vibrations of the  $\text{NH}_4^+$  ion remain unaltered during the formation  
of the activated state.

It is now possible to write an absolute rate expression for the pre-exponential linear decomposition rate factor of intermolecular orthorhombic  $\text{NH}_4\text{ClO}_4$ , identical in form to that used for sublimation of a non-linear molecule, namely

$$B_0 \text{ NH}_4\text{ClO}_4 = \left( \frac{\rho}{C^2 I} \right)^{1/3} \frac{kT}{h} \frac{\pi^{1/2} (8\pi^2 kT)^{3/2}}{\sigma \left[ 1 - \exp(-\theta/T) \right]^{-1}} \text{ cm sec}^{-1} \quad (48)$$

orthorhombic

where  $\rho$  = density of  $\text{NH}_4\text{ClO}_4$  (orthorhombic)  $\approx 1.95 \text{ g cm}^{-3}$

$\theta$  = characteristic temperature for lattice vibration frequency, assuming equal frequencies for translational and torsional oscillation  $\approx 350$   $^{\circ}\text{K}$

$\sigma$  = 12 = symmetry number of  $\text{ClO}_4^-$  ion

$I$  = moment of inertia of  $\text{ClO}_4^-$  ion =  $1.57 \times 10^{-38}$   $\text{g cm}^{-2}$

$T$  = average temperature = 501  $^{\circ}\text{K}$

Insertion of the above numerical constants into equation (48) yields

$$B_0 \text{ NH}_4\text{ClO}_4 \text{ (orthorhombic)} = 4 \times 10^7 \text{ cm sec}^{-1} \quad (49)$$

Theory

in reasonable agreement with the experimentally derived value of  $1.5 \times 10^8 \text{ cm sec}^{-1}$ .

A theoretical calculation of the activation energy for the linear decomposition of intermosaic orthorhombic  $\text{NH}_4\text{ClO}_4$  is not possible on the basis of present knowledge.

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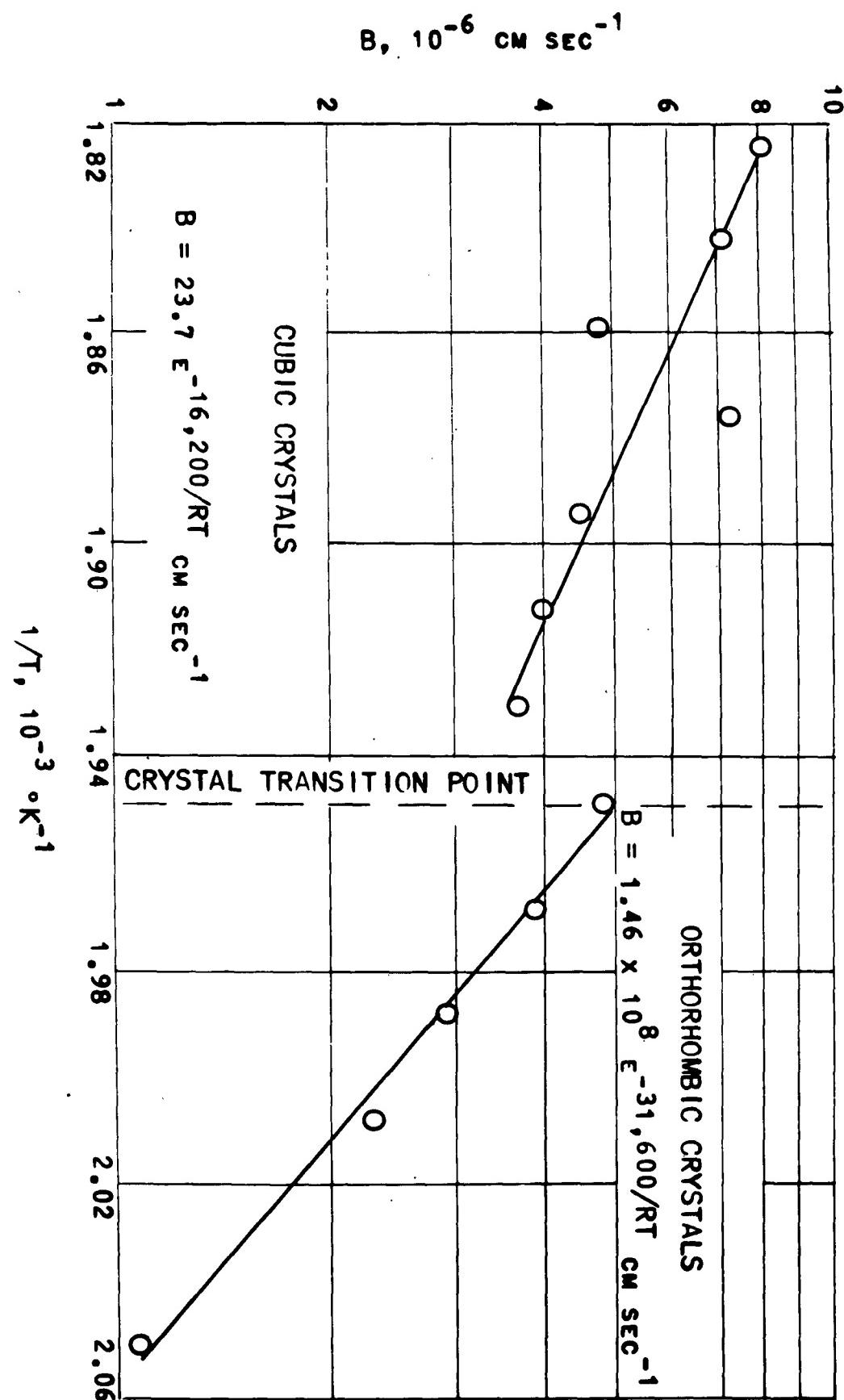
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12. Abstract: The experimental data of Bircumshaw and Newman are analyzed in terms of a linear rate of progression of the interface between residue and undecomposed crystal. Linear decomposition rates corresponding to given temperatures are derived directly from the maximum rate portions of the sigmoid curves of product pressure versus time. It is proposed that in the temperature range 220°C to 280°C, the decomposition interface travels exclusively through the disordered material between the mosaic blocks of the crystal and does not penetrate the interior of these blocks. Absolute rate treatments in the manner of Laidler, Glasstone, and Eyring are presented for each of the two crystal forms (orthorhombic and cubic). These treatments are similar to those proposed for the sublimation of ionic solids and the vaporization of solid ammonium chloride, respectively.



Rate of Linear Progression of Decomposition Interface in Ammonium Perchlorate as a Function of Temperature T

Figure 1

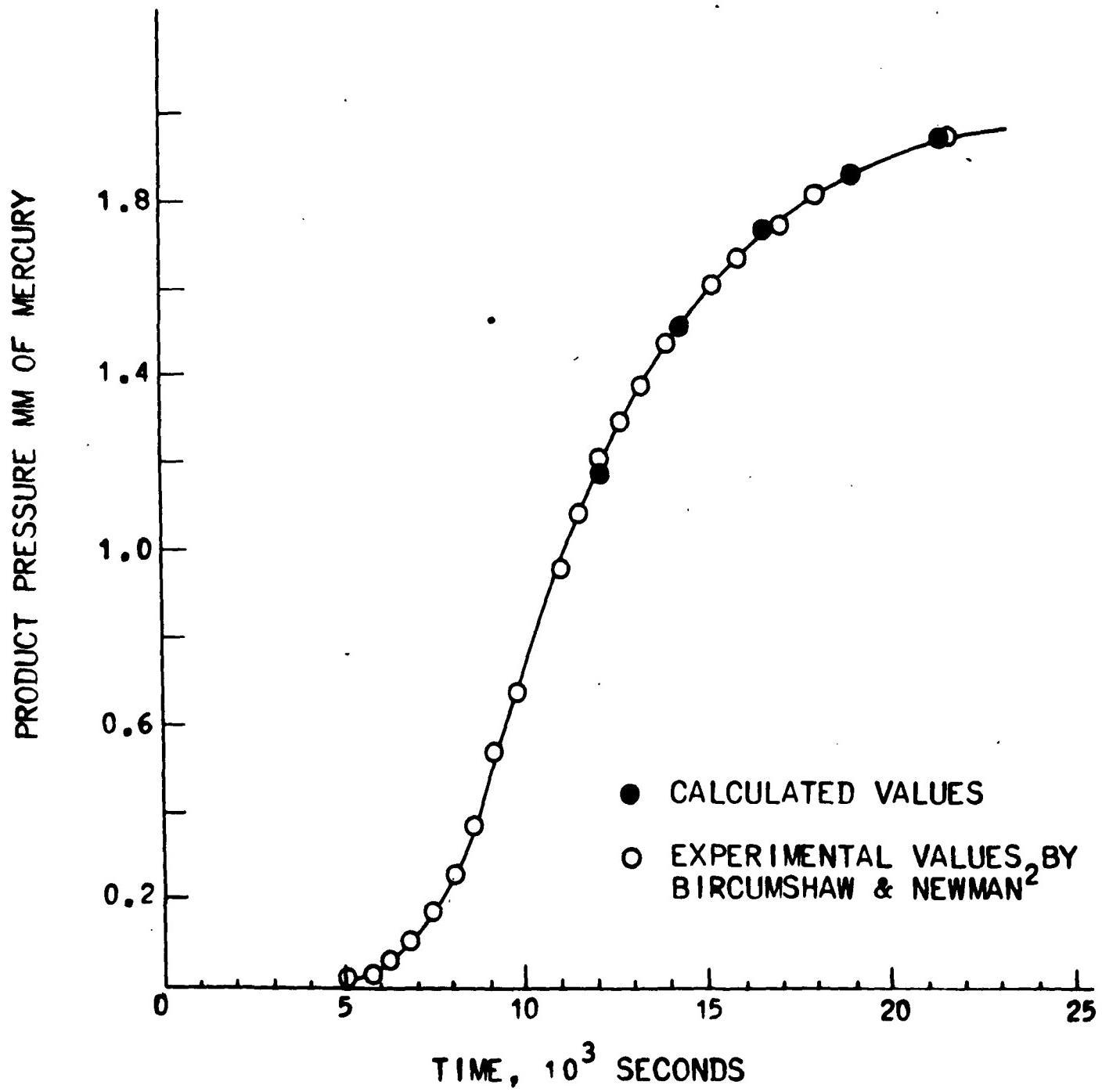
Ammonium Perchlorate Decomposition Curve ( $215^\circ\text{C}$ )

Figure 2

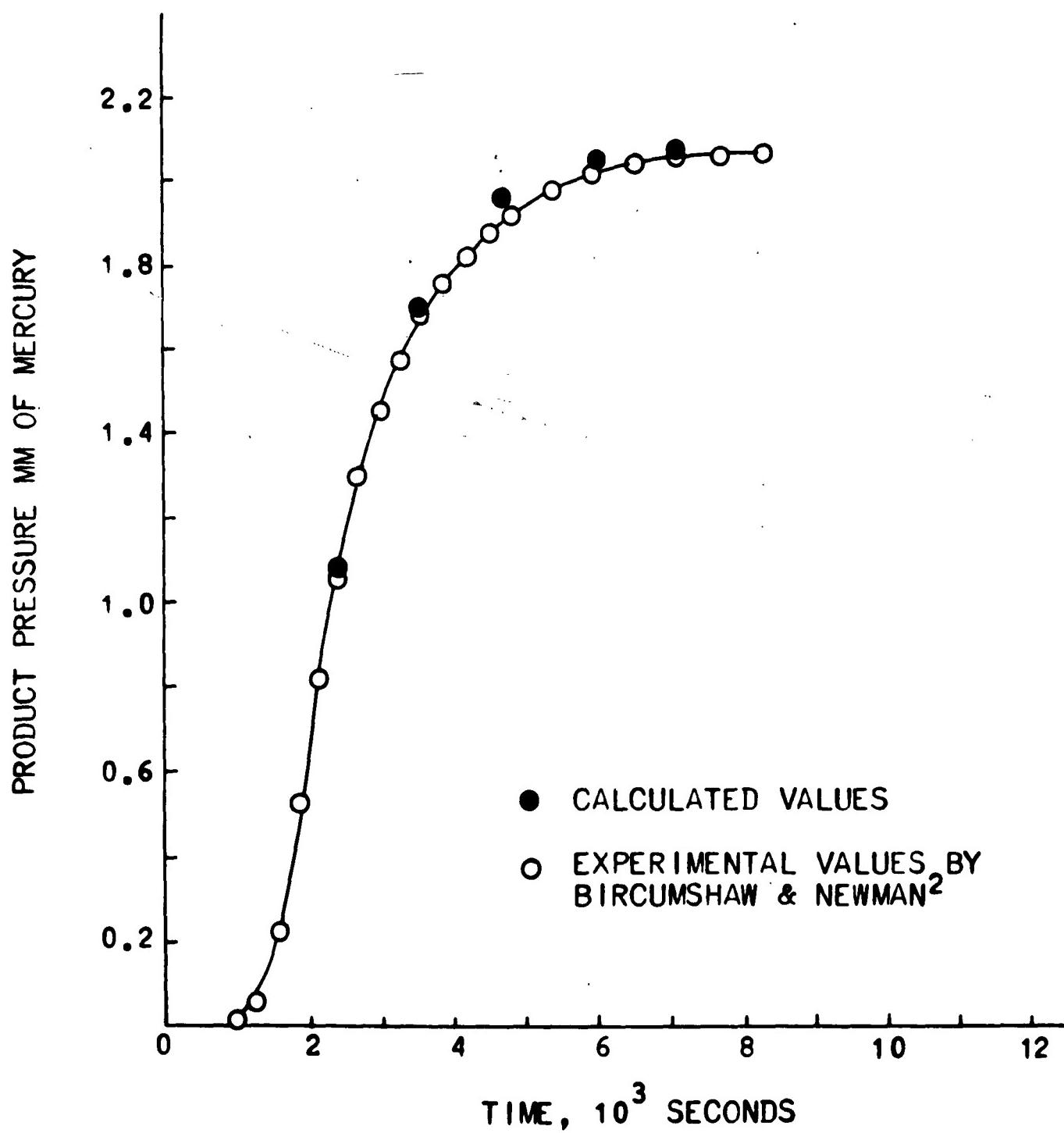
Ammonium Perchlorate Decomposition Curve ( $250^\circ\text{C}$ )

Figure 3

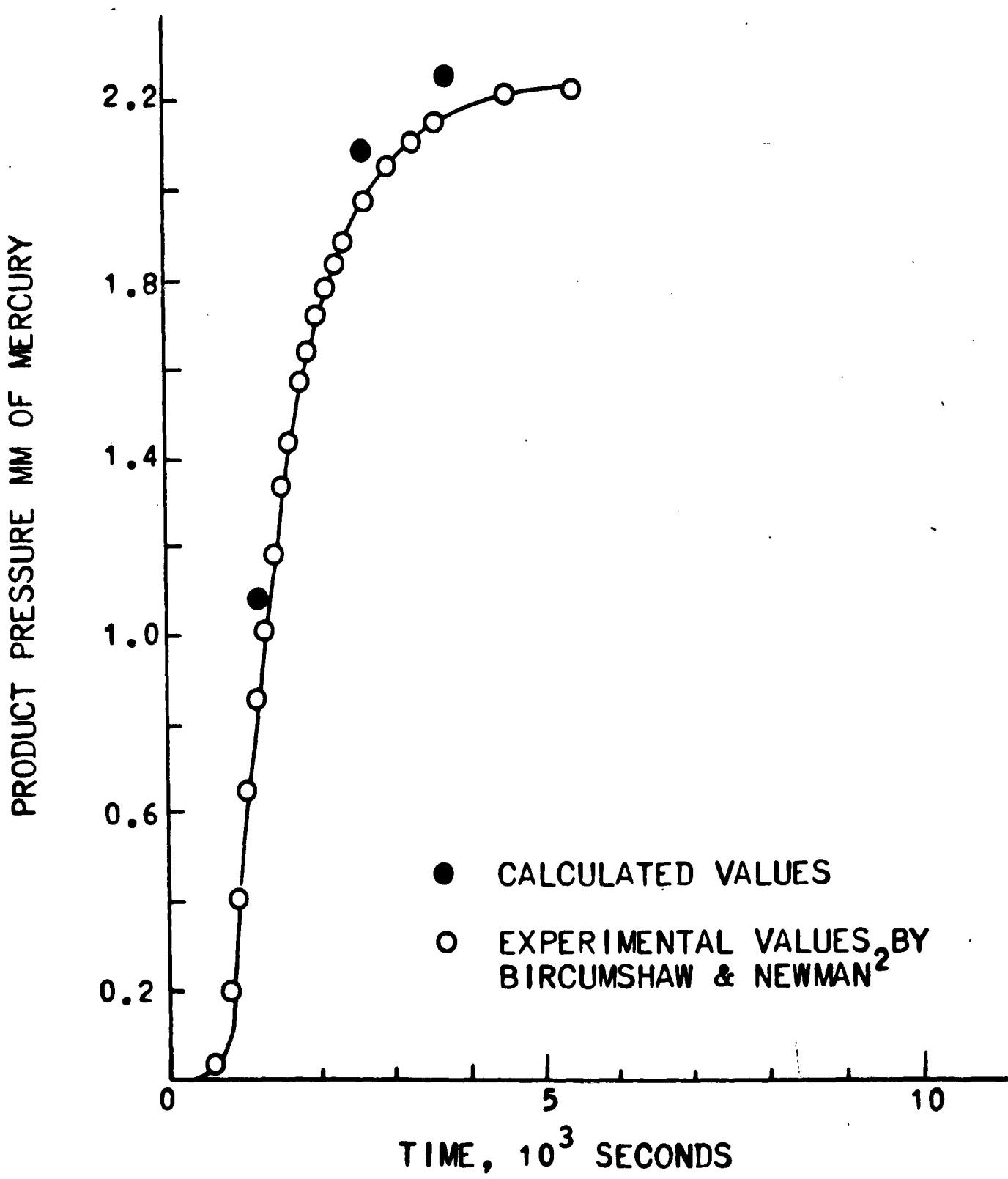
Ammonium Perchlorate Decomposition Curve ( $270^\circ\text{C}$ )

Figure 4

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